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Neutrinos can scatter electrons in water detectors through their magnetic moments and charge radii in addition to the charged and neutral currents channels. The recent solar neutrino charged current event rates announced by SNO with the earlier solar and atmospheric neutrino observations from Super-Kamiokande allows us to put upper bounds of $\mu < 10^{-9}\mu_B$ on neutrino magnetic moments and $< r^2 >< 10^{-31} cm^2$ on the neutrino charge radii . For the electron and muon neutrinos these bounds are comparable with existing bounds but for tau neutrinos these bounds are three orders of magnitude more stringent than earlier terrestrial bounds . These bounds are independent of any specific model of neutrino oscillations.

Among the electro-magnetic form factors of three neutrinos flavors, the magnetic moment and charge radius of the ν_τ are the least constrained in terrestrial experiments. This is because of the non-availability of a copious flux of ν_τ's in terrestrial sources like reactors and colliders. In contrast to the terrestrial sources, the Sun provides us with an intense beam of tau neutrinos which result from the conversion of the original electron neutrinos. Combination of several experimental observations can be used to infer the existence of ν_τ from the Sun and quantify its flux: (a) The recent observations of ν_e's at the Sudbury Neutrino Observatory (SNO) [1] establishes that the ^8B neutrinos are reduced to a fraction $P_{ee} = 0.347$ due to either vacuum oscillations or MSW conversion of solar neutrinos. The neutrino flux observed at SNO also implies that the earlier Super-Kamioka [2] flux measurements from the ν_e elastic scattering contained contribution from the neutral current also. This contribution is consistent with what is expected from the ν_e conversion to active flavours $\nu_{\mu,\tau}$. (b) Super-Kamiokande [3] observations of atmospheric neutrinos show that ν_μ oscillates with oscillation length $\sim 13000km$ (the earth diameter) and with maximal mixing ($Sin^2 2\theta_{23} \sim 1/2$). The absence of the matter effects in this oscillations [4] favour the conversion of ν_μ to ν_τ. The presence of the large amplitude $\nu_\mu - \nu_\tau$ oscillations imply that significant fraction of the solar neutrinos convert to ν_τ. Roughly, half of the converted fraction $(1 - P_{ee})$ of ν_e's contribute to ν_μ' and the remaining half to ν_τ' flux. Thus the neutrino beam from the sun (in the $5 - 15MeV$ energy range) appears as composed of the mixture of ν_e, ν_μ, ν_τ in approximately the ratio 0.347 : 0.326 : 0.326 respectively (the ratios being slightly different for lower energy neutrinos) at the earth. The one-third fraction of ν_τ's of the solar neutrino flux can therefore be utilized to study the electro-magnetic form factors of tau neutrinos.

The Super-Kamiokande experiment observes the elastic scattering (ES) of electrons in the water target which can be caused by both charged current (CC) and neutral current (NC) processes ($\nu_x + e^- \to \nu_x + e^-$ where $\nu_x = \nu_e, \nu_\mu$ or ν_τ). The SNO experiment uses a heavy water target and can differentiate the charged current reaction($\nu_e + d \to p + p + e^-$) from the neutral current ($\nu_x + d \to p + n + \nu_x$) and the electron scattering reactions. One can subtract the charged current rates of of SNO from the total elastic scattering rates of Super-K [3] to put bounds on scattering processes other than the charged and neutral current weak interactions. In this paper, we study the elastic scattering of electrons at SK due to the magnetic moments and charge radii of the solar neutrinos. Using the recent SNO results [1] along with the elastic scattering rates from Super-K [3] we obtain the following upper bounds (at $90\% C.L$) on neutrino electro-magnetic form factors (in the weak interaction basis):

Dirac moments

$$\begin{aligned} \mu_\tau, \mu_\mu &< 6.73\ (5.77)\ \times 10^{-10}\mu_B, \\ \mu_e &< 6.45\ (5.65)\ \times 10^{-10}\mu_B, \end{aligned} \tag{1}$$

Transition moments

$$\begin{aligned} \mu_{e\tau}, \mu_{e\mu} &< 4.66\ (4.04)\ \times 10^{-10}\mu_B, \\ \mu_{\mu\tau} &< 4.76\ (4.08)\ \times 10^{-10}\mu_B, \end{aligned} \tag{2}$$

Charge radii

$$\begin{aligned} |\langle r^2\rangle_{\nu_\tau}|, |\langle r^2\rangle_{\nu_\mu}| &< 2.08\ (1.53)\ \times 10^{-31} cm^2, \\ |\langle r^2\rangle_{\nu_e}| &< 6.86\ (5.26)\ \times 10^{-32} cm^2. \end{aligned} \tag{3}$$

where the main contribution to the errors is the theoretical uncertainty in the ^8B neutrino flux in the standard solar model [5]. The numbers displayed in the bounds (1-3) are calculated assuming an uncertainty of $\pm 20\%$ in the SSM neutrino flux. In the brackets we give the numbers assuming a SSM flux uncertainty of 5% .

These bounds are independent of whether the conversion mechanism of ν_e from the Sun is vacuum oscillations, or either large or small angle MSW [6] but they assume three light neutrinos. Bounds similar to above can be obtained even if ν_e mixing with sterile state consistent with present experiments [7] is allowed. Likewise, one obtains bounds of similar magnitudes if the solar neutrinos convert to anti- neutrinos through spin-flip in solar magnetic field [8].

Our bound on the tau neutrino Dirac magnetic moment is about three orders of magnitude more stringent than the previous best bound $\mu_\tau < 5.4 \times 10^{-7}\mu_B(90\% C.L)$ [9] obtained by a terrestrial experiment (from $\nu_\tau e$ scattering by tau neutrinos obtained from D_s decay) . The bound on μ_{ν_μ} is comparable with the bound $\mu_{\nu_\mu} < 7.4 \times 10^{-10}\mu_B$ obtained from $\nu_\mu e$ elastic scattering measurements at LAMF [10]. Our bound on μ_{ν_e} is weaker by a factor of five compared to the earlier bound $\mu_{\nu_e} < 1.5 \times 10^{-10}\mu_B$ obtained by analysis of the spectral distortion of electron scattering by solar neutrinos at Super-K [11].

The charge radius of ν_e has been bounded by the LAMF experiment ($< r^2 >= (0.9 \pm 2.7)10^{-32}cm^2$) and for the muon neutrino the bound from scattering experiment [12] is ($< r^2 >_\mu < 0.6 \times 10^{-32}cm^2$). To our knowledge there are no bounds on the charge radius of τ neutrinos from scattering experiments.

Our method is similar to that of [13] who also used the total Super-K scattering rates to put bounds on neutrino electro-magnetic form factors. Our analysis differs from [11] and [13] in the following ways:(a) we have included the recent SNO CC rates to subtract out the weak interaction part from the Super-K elastic scattering rate. This avoids assumption [13] about the relative strength of the charged and neutral current contribution at Super-K (b) our analysis is more conservative as we have also included a possible 20% error in the theoretical ^8B flux prediction [5] which as emphasized in [7] is the main source of uncertainty in extracting bounds from Super-K and SNO observations , and mainly (c) we have used the results from atmospheric neutrinos to establish that $\sim 1/3$ of the solar neutrino flux consists of ν_τ which enables us to put much more stringent bounds on the ν_τ magnetic moment and charge radius than was possible in earlier terrestrial experiments.

From the analysis of atmospheric neutrinos [2] and the ν_e disappearance experiment at CHOOZ [14] we can write the mixing matrix U for the three neutrino generations as

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_1 & s_1 & 0 \\ -c_2 s_1 & c_2 c_1 & s_2 \\ -s_2 c_1 & s_2 c_1 & c_2 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \tag{4}$$

Here (c_1, s_1) denote the mixing relevant for the solar neutrinos and (c_2, s_2) are the mixings relevant for the atmospheric neutrinos. The U_{e3} element is set to zero from the CHOOZ observation that disappearance of ν_e is less than 4% (with sensitivity to $\delta m^2 \sim 10^{-3}eV^2$ in the atmospheric range), which implies that $U_{e3}^2(1 - U_{e3}^2) < 0.01$. Using this constraint with the atmospheric neutrino observation of maximal mixing between ν_μ and ν_τ ($U_{\mu 3}^2 = U_{\tau 3}^2 = 0.5$) then (by unitarity) implies that $U_{e3}^2 < 0.01$. We have set the U_{e3} entry in (4) to be zero for simplicity (the 1% error incurred here is negligible compared the experimental errors ($\sim$ 5%) and theoretical flux uncertainty (20%)).

The conversion probability to ν_τ and ν_μ of ν_e produced in the solar core can be derived using (4) and turns out to be of the form

$$\begin{aligned} P_{e\mu} &= c_2^2 \, (1 - P_{ee}), \\ P_{e\tau} &= s_2^2 \, (1 - P_{ee}) \end{aligned} \tag{5}$$

The assumptions made in deriving (5) are (a) in case of vacuum oscillations , the oscillation length scale l_{23} associated with the (ν_2, ν_3) mass difference (δm_{23}^2) is smaller than the earth sun distance or (b) in case of matter induced conversion of ν_e , the matter potential in the sun $\sqrt{2}G_F N_e << \delta m_{23}^2/2E$ and the oscillation length $l_{23} << R_\odot$. These conditions are met by the atmospheric neutrino oscillation length scale $l_{23} \sim 2R_\oplus = 13,000km$ with the associated mass scales $\delta m_{23}^2 \sim 10^{-3}eV^2$ [2]. The form of eq.(5) is independent of the mechanism of the solar ν conversion but the expression for P_{ee} depends on the specific mechanism which could either be vacuum oscillations or large or small angle MSW depending on the (ν_1, ν_2) mass difference. Simultaneous use of the SNO and SK results allows direct extraction of P_{ee} from experiments and makes the following analysis independent of whether the specific mechanism of conversion MSW or VO. The analysis differs if there is conversion to antineutrinos by some resonant helicity flip mechanism or if there is a significant conversion to sterile neutrinos. These two possibilities are discussed separately in the final sections.

Supposing the ν_e produced in the Sun are converted to ν_μ's and ν_τ' with probabilities given by (5) , the rates of elastic scattering events at Super-K and charged current events at SNO can be written as

$$\begin{aligned} \frac{\phi_{SK}^{ES}}{\phi_{SSM}} &= \langle P_{ee} \rangle + \langle \frac{\sigma_{\nu_\mu}}{\langle \sigma_{\nu_e} \rangle}(1 - P_{ee}) \rangle + \langle \frac{\sigma_{\nu_e}^\gamma}{\langle \sigma_{\nu_e} \rangle} P_{ee} \rangle \\ &+ \langle \frac{\sigma_{\nu_\mu}^\gamma}{\langle \sigma_{\nu_e} \rangle} c_2^2 (1 - P_{ee}) + \langle \frac{\sigma_{\nu_\tau}^\gamma}{\langle \sigma_{\nu_e} \rangle} s_2^2 (1 - P_{ee}) \rangle \end{aligned} \tag{6}$$

and

$$\frac{\phi_{SNO}^{CC}}{\phi_{SSM}} = \langle P_{ee} \rangle \ , \tag{7}$$

where σ_{ν_e} (σ_{ν_μ}) denote the weak (ν_e e) ((ν_μ e) and (ν_τ e)) elastic scattering cross sections. The photon mediated scattering by a neutrino ν_α , is denoted by $\sigma_{\nu_\alpha}^\gamma$ (where $\alpha = e, \mu, \tau$). These cross sections are proportional to the diagonal or transition magnetic moment $\mu_{\alpha\beta}$ or the charge radii $< r^2 >_\alpha$ of ν_α.

The cross section for the elastic scattering $\nu_\alpha + e^- \rightarrow \nu_\beta + e^-$ due to neutrino magnetic moment is given by the expression [15]

$$\frac{d\sigma_{\nu_\alpha}^\gamma}{dT} = \mu_{\alpha\beta}^2 \, (\alpha_{em})(\frac{1}{T} - \frac{1}{E_\nu}) \tag{8}$$

where T is the recoil energy of the scattered electron. The magnetic moments are defined in the flavour basis corresponding to the diagonal charged currents and differ from the corresponding moment in the neutrino mass basis [11]. The conical brackets in (6-7) denote averaging over the neutrino energy spectrum from the sun and the detector response function of the detector. We make use of the observation [1] and [3] that P_{ee} is energy independent in the neutrino energy range probed in these experiments. This allows the simplification $\langle \sigma P_{ee} \rangle \simeq \langle \sigma \rangle \langle P_{ee} \rangle$ in (6). We average the cross sections for the weak interaction scatterings and the magnetic moment (and charge radius) mediated scatterings by using the analytical form for the ^8B spectrum of solar neutrinos given in [16]. We incorporate the error involved in the measurement of the recoil electron energy T by averaging the expressions over a detector response function $r(T, T')$ given in [17]. We chose the threshold energy to be $E_\nu \geq 8.5 MeV$ since as shown by [17] with this threshold the rates at Super-K and SNO can be compared (although the two experiments have different thresholds and different detector responses) and we take the upper limit for $E_\nu = 15 MeV$. The averaged magnetic moment scattering cross section (8) turns out to be

$$\langle \sigma^\gamma (\nu_\alpha e^- \to \nu_\beta e^-) \rangle = \kappa^2_{\alpha\beta} \; 4.877 \times 10^{-27} cm^2 \tag{9}$$

where $\kappa_{\alpha\beta}$ are the diagonal or transition magnetic moments in units of the Bohr magnetron . The average values of the ν_e and ν_μ weak elastic scattering cross sections (10) with e^- turn out to be

$$\begin{aligned} \langle \sigma_{\nu_e} \rangle &= 9.108 \times 10^{-45} cm^2, \\ \langle \sigma_{\nu_\mu} \rangle &= 1.343 \times 10^{-45} cm^2. \end{aligned} \tag{10}$$

Substituting (9) and (10) in (6) and (7) and using the experimental results for the elastic scattering rates from Super-K [3]

$$\phi^{ES}_{SK} = (0.451 \pm 0.017) \times \phi_{SSM} \tag{11}$$

and the charged current rates from SNO [1]

$$\phi^{CC}_{SNO} = (0.347 \pm 0.029) \times \phi_{SSM} \tag{12}$$

along with the theoretical solar neutrino flux prediction [5]

$$\phi_{SSM} = (5.05 \times 10^{-6} cm^{-2} s^{-1}) + 20\% - 16\% \tag{13}$$

and with the experimental determination of the (ν_2, ν_3) mixing angle from atmospheric neutrinos [2]

$$Sin^2\theta_2 = 0.5 \pm 0.05 \tag{14}$$

we obtain the following limits on neutrino magnetic moments (with the errors shown at one σ).

Dirac moments

$$\begin{aligned} \mu^2_\tau = \mu^2_\mu &= (4.42 \pm 24.92) \times 10^{-20} \mu^2_B, \\ \mu^2_e &= (4.16 \pm 22.84) \times 10^{-20} \mu^2_B, \end{aligned} \tag{15}$$

Transition moments

$$\begin{aligned} \mu^2_{e\tau} = \mu^2_{e\mu} &= (2.14 \pm 11.92) \times 10^{-20} \mu^2_B, \\ \mu^2_{\nu_{\mu\tau}} &= (2.11 \pm 12.46) \times 10^{-20} \mu^2_B. \end{aligned} \tag{16}$$

The transition moments have better bounds as they contribute to the elastic scattering (6) through two channels whereas the Dirac moments contribute to one term at a time in (6). The bounds (15) and (16) translate to the upper bounds (1-2) at $90\% C.L$. The largest source of error in obtaining these bounds is the large uncertainty -16% to $+20\%$ in the ^8B flux prediction of the standard solar model [5]. If the ^8B flux can be determined from solar neutrino experiments themselves to an accuracy of $\pm 5\%$ then the bounds on the magnetic moments improve as shown by bracketed numbers in equations (1-3).

Using a similar analysis one can establish bounds on the charge radius scattering by neutrinos. This scattering unlike the neutrino magnetic moment one preserves the helicity of the neutrinos and it can therefore interfere with the weak interaction elastic scattering amplitude. The contribution of this interference term to the total elastic scattering cross section for the $(\nu_\alpha \; e)$ scattering is given by [15]

$$\begin{aligned} \frac{d\sigma^\gamma_{\nu_\alpha}}{dT} &= \langle r^2 \rangle_\alpha \; \frac{\sqrt{2}}{3} G_F \alpha_{em} m_e ((g_V + g_A) \\ &+ (g_V - g_A)(1 - \frac{T}{E_\nu})^2 - g_V \frac{m_e T}{E^2_\nu}) \end{aligned} \tag{17}$$

Following the same averaging procedure as for the magnetic moment case we find the expression for the flux and detector response averaged cross sections due to charge radius scattering are

$$\begin{aligned} \langle \sigma^\gamma_{\nu_e} \rangle &= 2.96 \times 10^{-14} \langle r^2 \rangle_{\nu_e}, \\ \langle \sigma^\gamma_{\nu_\mu, \nu_\tau} \rangle &= -1.06 \times 10^{-14} \langle r^2 \rangle_{\nu_\mu, \nu_\tau}. \end{aligned} \tag{18}$$

Using the averaged cross sections (18) in equation (6) and using the experimental rates (11-14) and theoretical prediction (13) we find that the limits on neutrino charge radii are

$$\begin{aligned} \langle r^2 \rangle_{\nu_\mu} = \langle r^2 \rangle_{\nu_\tau} &= (-2.03 \pm 11.46) \times 10^{-32} cm^2, \\ \langle r^2 \rangle_{\nu_e} &= (0.686 \pm 3.77) \times 10^{-32} cm^2. \end{aligned} \tag{19}$$

These bounds can be converted to upper bounds on the neutrino charge radii as given in (3) .

Bounds in case of conversion to sterile neutrinos: The analysis so far assumed only three light neutrinos. While this possibility seems most favoured, significant admixture of sterile state is still allowed [7]. Suppose only a fraction $Sin^2\alpha$ of the converted solar neutrinos are active (ν_μ or ν_τ). In that case the expression

(6) must be modified by replacing the factor $(1-P_{ee})$ by $Sin^2\alpha(1-P_{ee})$. As shown in [7] one can combine the average rates from the Cl and Ga experiments with the SK and SNO results to limit put limits on $Sin^2\alpha$. The SSM flux prediction along with the central values of experimental rates implies [7] no sterile mixing, i.e. $Sin^2\alpha = 1$. However at 1σ, a $Sin^2\alpha$ as small as 0.3 is allowed in case of the SSM. It is still possible to obtain significant bound on magnetic moments in this case. We illustrate this taking a specific case of $Sin^2\alpha = 0.3$ and 20% uncertainty in the SSM flux. The bounds on the neutrino EM form factors turn out in this case to be (with $90\% C.L$)

Dirac moments

$$\mu_\tau,\ \mu_\mu < 1.68\times 10^{-9}\mu_B, \quad \mu_e < 0.865\times 10^{-9}\mu_B, \tag{20}$$

Transition moments

$$\mu_{e\tau},\ \mu_{e\mu} < 7.63\times 10^{-10}\mu_B, \quad \mu_{\nu_{\mu\tau}} < 1.18\times 10^{-9}\mu_B, \tag{21}$$

Charge radii

$$|\langle r^2\rangle_{\nu_\mu}|,\ |\langle r^2\rangle_{\nu_\tau}| < 1.29\times 10^{-30}cm^2, \quad |\langle r^2\rangle_{\nu_e}| < 1.23\times 10^{-31}cm^2. \tag{22}$$

Bounds for RSFP solution: In case the correct solution of the solar neutrino problem is resonant spin flip in the solar magnetic field then also the same procedure we have followed can be applied. If ν_e convert to $\bar{\nu}_\mu$ due to resonant spin-flip (RSFP) [8] in the sun then again due to $\bar{\nu}_\mu, \bar{\nu}_\tau$ mixing we will have neutrinos from the sun in the ratio $\nu_e : \bar{\nu}_\mu : \bar{\nu}_\tau :: 0.347 : 0.326 : 0.326$. The ν_μ, e weak interaction cross section in (6) will be replaced by the $\bar{\nu}_\mu, e$ cross section whose value (after averaging over the ^8B spectrum ([16]) and the detector response function [17]) turns out to be

$$\langle\sigma_{\bar{\nu}_\mu}\rangle = 1.014\times 10^{-45}cm^2 \tag{23}$$

and the charged radii cross sections for ν_μ and ν_τ in (18) have to be replaced by their corresponding anti-particle cross sections,

$$\langle\sigma^\gamma_{\bar{\nu}_\mu,\bar{\nu}_\tau}\rangle = 0.895\times 10^{-14}\langle r^2\rangle_{\bar{\nu}_\mu,\bar{\nu}_\tau}. \tag{24}$$

Making these changes in (6) and following the same procedure as above we obtain the following bounds on the E-M form factors of the neutrinos ($90\% C.L$):

Dirac moments

$$\mu_\tau,\ \mu_\mu < 0.767\times 10^{-9}\mu_B, \quad \mu_e < 0.721\times 10^{-9}\mu_B. \tag{25}$$

Transition moments

$$\mu_{e\tau},\ \mu_{e\mu} < 0.524\times 10^{-9}\mu_B, \quad \mu_{\nu_{\mu\tau}} < 0.542\times 10^{-9}\mu_B, \tag{26}$$

Charge radii

$$|\langle r^2\rangle_{\bar{\nu}_\mu}|,\ |\langle r^2\rangle_{\bar{\nu}_\tau}| < 3.21\times 10^{-31}cm^2, \quad |\langle r^2\rangle_{\nu_e}| < 0.858\times 10^{-31}cm^2. \tag{27}$$

Although the RSFP solution is sensitive to the values of transition magnetic moments and solar magnetic field, the above analysis did not make use of the dynamics of RSFP and only assumed that P_{ee} is reduced to experimental value through the conversion of ν_e to $\bar{\nu}_\mu$ or $\bar{\nu}_\tau$ inside the Sun.

Conclusions : Measurements of electro-magnetic form factors of tau neutrinos in terrestrial experiments is limited by the absence of a calibrated copious ν_τ source. We have shown that the solar neutrino beam with roughly equal mixture of all the neutrino species can be used for putting bounds on τ neutrinos which are far more stringent than bounds from other terrestrial experiments. Bounds on neutrino properties can be put from cooling rates of supernovae and helium stars [18] are stronger though less reliable than scattering experiments from calibrated sources.

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